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Vapor Cloud Explosion Live Test and Data Analysis Development Program

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Abstract

Vapor Cloud Explosions (VCE), an ever-present threat to the petroleum refining industry, create hazards to employees, equipment and production capabilities. To mitigate the effect of these hazards, effective designs for structural and non-structural components must be developed and confirmed via experimental validation to ensure the safety and performance of the facility and its occupants. Current methodologies for full-scale VCE performance testing involve the use of large quantities of high explosives set at a large standoff distance to achieve the time durations common in VCE events. While effective in achieving the peak pressures involved, these tests do not adequately characterize the full behavior of the time-dependent loading conditions and other effects seen in VCE events, such as enhanced turbulence, degree of confinement and the reactivity of unburned materials. The explosive testing community recognizes that current testing methods do not fully characterize the loading behavior and that only a small number of large-scale VCE tests have been conducted by various commercial and government agencies. Unfortunately, most of the work has been in support of counterterrorism efforts, making the test data unavailable to the petroleum industry.

Background

Vapor Cloud Explosions (VCE), an ever-present threat to the petroleum refining industry, create hazards to employees, equipment and production capabilities. To mitigate the effect of these hazards, effective designs for structural and non-structural components must be developed and confirmed via experimental validation to ensure the safety and performance of the facility and its occupants. Current methodologies for full-scale VCE performance testing involve the use of large quantities of high explosives set at a large standoff distance to achieve the time durations common in VCE events. While effective in achieving the peak pressures involved, these tests do not adequately characterize the full behavior of the time-dependent loading conditions and other effects seen in VCE events, such as enhanced turbulence, degree of confinement and the reactivity of unburned materials. The explosive testing community recognizes that current testing methods do not fully characterize the loading behavior and that only a small number of large-scale VCE tests have been conducted by various commercial and government agencies. Unfortunately, most of the work has been in support of counterterrorism efforts, making the test data unavailable to the petroleum industry. See Section 10 for a description of current models and descriptions, as well as Section 11 for resources available for research purposes.

Objectives

The goal of this research program is to conduct full-scale VCE experiments that generate comprehensive blast behavior and structural response data. Commercial and academic team members will have access to this data in order to further enhance the industry standards for design and modeling. Improvements in VCE blast behavior understanding and structural response developed from this program will be provided to outside commercial interests through speaking engagements and publications by team members.

The experimental program will be rigorously developed using small-scale experiments as initial benchmarks for generation of the full-scale methodology. Additionally, commercially available mitigation technologies, such as free-standing Blast Resistant Modules (BRM), blast resistant doors, window glazing, fiber technologies and other retrofit technologies will be exposed to direct blast conditions. Post-blast evaluation, documentation, and dissemination of results to team members as well as participating commercial entities will round out each physical test.

Advanced computational fluid dynamic (CFD) models utilize fundamental physics to accurately represent real geometry. These predictive tools have limitations requiring further development and testing to be fully realized. Model development can be furthered and refined with the use of repeatable, well-defined, detailed experiments that focus on key aspects of the physics of explosions. Real-world testing will provide the ability to calibrate code that reflects reality.

Definitions and Historical Examples

A vapor cloud explosion occurs when a sufficient amount of flammable or combustible material is released, mixes with air, and is ignited by a variety of potential sources. Some causes of the release of vapor or gaseous fuel include:

- Rapid discharge of flammable vapor
- Release of flammable liquid stored under pressure

If the flammable vapor cloud is ignited, it may simply burn, but has the capability to initiate a deflagration (violent, explosive burning) and the potential to transition into a full detonation, producing a blast wave, which can cause major destruction over a large distance. This is particularly true for releases in congested or confined areas, for vapor clouds that have drifted into such areas, and for reactive materials. In addition, heat from the fireball can cause significant injury or damage.

Some of the worst disasters in the history of the chemical process industry have been vapor cloud explosions. Some examples include:

- May 1988, Diamond, LA (7 fatalities, 48 injuries, $700+ million in financial losses)[17]
    - A pipeline, which was eight inches in diameter, was corroded and allowed 20,000 pounds of C-3 hydrocarbons to escape. A vapor cloud formed and ignited causing a major explosion. Damage from the explosion radiated one mile from the center of the explosion and debris could be found as far as five miles from the center of the explosion. The explosion caused a fire to burn for eight hours at the oil refinery before it was brought under control. Chemicals that escaped during the explosion resulted in cars and homes being covered by a black film. The explosion released 159 million toxic chemicals into the air, which led to widespread damage and the evacuating on 4,500 people.
- October 1989, Pasadena, TX (23 fatalities, 314 injuries, $1.4+ billion in financial losses)[15]
    - The accident resulted from a release of extremely flammable process gases that occurred during regular maintenance operations on one of the plant's polyethylene reactors. More than 85,000 pounds (39 t) of highly flammable gases were released through an open valve almost instantaneously.
    - During routine maintenance, isolation valves were closed and compressed air hoses that actuated them physically disconnected as a safety measure. The air connections for opening and closing this valve were identical, and had been improperly reversed when last re-connected. As a result, the valve would have been open when the switch in the control room was in the "valve closed" position. After that, the valve was opened when it was expected to stay closed, and finally passed the reactor content into air. A vapor cloud formed and traveled rapidly through the polyethylene plant. Within 90 to 120 seconds, the vapor cloud came into contact with an ignition source and exploded with the force of 2.4 tons of TNT.[1] Ten to fifteen minutes later, that was followed by the explosion of the 20,000-US-gallon (76,000 L) isobutane storage tank, then by the catastrophic failure of another polyethylene reactor, and finally by other explosions.
- March 2005, Texas City, TX (15 deaths, 180 injures, $3.1+ billion in financial losses)[13]
    - During maintenance shut-down, an isomerization unit was being restarted after 2 weeks of down-time. Due to various reasons a flammable cloud of hydrocarbons formed and spread over a large part of the unit. The cloud was ignited by a running engine of a utility truck, thus sparking an initial explosion of the “unconfined vapor cloud explosion” type, followed by a fire.
    - The victims were not working directly inside the refinery's isomerization unit but were actually attending a scheduling meeting on the shutdown of the high-performance cracking machine within one of the prefabricated premises installed for subcontractors. These premises, located about 300ft from the isomerization unit were heavily damaged by the explosion and subsequent fire.
- December 2005, Buncefield, England (43 injuries, €750+ million in financial losses)[14]
    - Due to erroneous information provided by a level sensor/indicator, an unleaded gasoline tank filled via pipeline overflowed and a cloud formed over the entire site. The cloud moved beyond the company’s perimeter and detonated with subsequent fires.
    - Other companies located within the industrial zone also sustained substantial damage: some twenty businesses employing a total of 500 personnel were

destroyed, while another sixty firms accounting for 3,500 jobs incurred major damage.

Program Organization

The research program will be conducted by a joint academic and industry team with expert knowledge spanning various areas of blast, explosives, testing, analysis, and structures. The collaborative approach will ensure that the tests will be conducted efficiently and safely using proven processes and the best practices established and utilized by the professional members of our team.

PROGRAM MANAGEMENT

Advanced Materials Division SCRA Applied R&D (SCRA)

SCRA will serve as the prime contractor for the effort, providing programmatic oversight and interfacing with commercial clients.

SCRA delivers technology-based solutions to complex challenges - primarily for federal agencies and over two hundred corporations world-wide. SCRA combines expertise in target markets, a robust network of trusted partners and access to state of the art research laboratories to develop programs to improve capability and lower costs of client products and processes. SCRA carries a long history of organizing and executing Federal R&D projects. SCRA's active contract value of R&D portfolios is over $2 billion.

EDUCATIONAL

Texas A&M University / Mary Kay O'Connor Process Safety Center (PSC)

PSC will serve as a key technical advisor for test planning and execution. PSC will interface with industry representatives to determine the most useful test set-ups and provide input on the layout of the experiments. PSC brings a vast knowledge of safety expertise to ensure blast testing is well-planned and safely executed.

California Institute of Technology (Caltech)

Dr. Joseph Shepherd of Caltech will provide technical expertise on the initiation properties and Deflagration to Detonation Transition (DDT) of the gaseous blends selected for testing in the program.

University of California – San Diego / Englekirk Center Powell Structural Research Lab (UCSD)

UCSD will provide a laboratory setting for simulator testing and experiments as they relate to structural model development. Dr. Gil Hegemier, PE will be the Principal Investigator at UCSD.

COMMERCIAL

Applied Research Associates (ARA)

ARA will serve as primary test organizer and performer. Small scale testing will occur at the East Range Test Facility near Denver, CO. The full-scale testing effort will occur at a selected ARA large-scale test facility. ARA will supply all instrumentation equipment and will be responsible for test set-up, execution and data collection.

ARA will provide post-test modeling analysis using standard predictive codes such as "Shamrock" and proprietary fast-running software to post-process the transient pressure profile of the blast test, yielding a comprehensive global view of the instrument data.

ARA has 35 years of experience in conducting large-scale explosive research and modeling programs for the Department of Defense, Department of Homeland Security, Department of Justice and various commercial clients.

Jacobs Engineering (Jacobs)

Jacobs Engineering possesses unique capabilities in transient computational analysis that can be applied to blast modeling. These tools are extremely powerful in simulating the transient pressure field occurring in large-scale vapor cloud explosion testing. This in-house software tool, known as "JUSTUS", provides a simulated global view of test event pressure/time history that complements the data and is useful for examining, comparing, and understanding test data findings. The JUSTUS program also offers potential capabilities for subsequent analysis of petroleum industry client facilities for blast loading and mitigation assessment.

Protective Technologies LLC (PT), a Harrison, Walker & Harper Company

PT developed the original concept for this program as a method for designing new VCE modeling programs based on real-world live testing. PT is responsible for the marketing of the program to various entities for funding to support the program.

PT will support construction of various components during live testing, furnish blast resistant structures for evaluation, and focus on supporting software development of VCE models and how it is applied to facilities and structures.

Program Description & Timeline

The research program will consist of several phases of experiments and data analysis/modeling. The experimental series is designed in such a way that initial small-scale investigational studies are conducted to ensure full-scale tests are efficient, safe, and successful.

This program is being developed to start Phase I as soon as funding has been allocated. Each phase will be dependent on reaching a minimum funding level before work will start. In order to achieve the minimum desired level of success through Phase III, approximately $1,000,000 in funding must be sourced.

PHASE I- LABORATORY SCALE RESEARCH AND SMALL SCALE INITIATION TESTING

Selection of potential gas mixtures, small scale (<10 lb TNT equivalent) initiation and DDT investigations.

This test achieves our goal of validating the initiation methodology and gas mixtures to be used in following phases. Additionally, we will simulate the test using JUSTUS to calibrate and validate simulation accuracy.

This phase will involve all academic and commercial members in the development of testing protocol, setup, and instrumentation required to provide the benchmark for subsequent testing phases. This phase is intended to be proof-of-concept.

Performance Location: East Range Test Facility, Colorado

Length: 12 to 16 weeks

PHASE II- MEDIUM SCALE INITIATION TESTING

Proof of concept evaluation for basic set-up and initiation characteristics for medium scale (<1000 lb TNT equivalent) test events.

This portion of the test program allows us to verify the scalability of the initiation methodology and gas mixtures.

This phase will take the proof-of-concept results and expand the blast size to provide a more robust and final proof-of-concept before initiating a full-scale blast.

Performance Location: ARA medium-scale or large-scale test facility

Length: 3 to 6 weeks

PHASE III- FULL SCALE FREE FIELD TESTING

Full Scale (<10,000 lb TNT equivalent) test events in free field arena with full instrumentation, diagnostic equipment and select mitigation test articles.

The purpose of this test is to provide data for analysis and dissemination to all members involved. The data will be used to calibrate/validate multiple computational predictive models.

This phase will be a full-scale blast test with instrumentation.

Performance Location: ARA large-scale testing facility

Length: 8 to 12 weeks

PHASE IV- FULL SCALE TESTING WITH COMPLETE ARENA SET-UP

Full Scale (<10,000 lb TNT equivalent) test events with surrogate processing equipment and complete mitigation test articles to simulate refinery operating conditions.

This test will provide data for analysis and dissemination to all members involved. The data will be used to calibrate/validate multiple computational predictive models and the structural responses.

This phase will include the construction of an arena setup, to include commercial products. The objective of this phase is to conduct a full-scale blast with varying surfaces, blockage, and reflective surfaces to provide a realistic environment scenario and data capture. Data will be recorded and analyzed.

Performance Location: ARA large-scale testing facility

Length: 12 to 16 weeks

PHASE V – DATA ANALYSIS & MODELING ADVANCEMENT

The data will be analyzed and disseminated to all members involved. The data will be used to calibrate/validate multiple computational predictive models, such as performed by ARA and Jacobs, for both VCE environment behavior, as well as predictive models for structural response. Such models are vital for the future development of design and industry retrofit strategies.

This phase will be a full data review and software modeling effort intended to calibrate and verify research and commercial software tools based on live testing data.

Length: 12 to 18 weeks

Instrumentation Suite

ARA will execute the full scale test program with a complete range of diagnostic equipment, including full arrays of reflected/incident pressure transducers, high-speed digital Phantom cameras, high-speed imbedded video cameras, and standard-speed HD video cameras. In addition, accelerometers, impulse gauges, heat flux gauges, high-speed thermocouples, fast gas sampling systems, and ground shock probes will complete the instrumentation set-up.

Petroleum Industry Customers

Commercial and/or industry representatives may join the Vapor Cloud Explosion (VCE) Consortium by paying membership dues and participating regularly in conference calls and annual meetings. The membership dues will be used to cover expenses incurred by VCE Technical performers such as Georgia Tech, UCSD, TAMU PSC, Caltech, ARA, Jacobs, PT, and SCRA in the test planning, set-up, execution, analysis and administrative efforts.

Data

All data collected from free field and general pressure instrumentation and diagnostic equipment will be freely shared with all our collaborating industry partners and academic team members. Data will be formally transmitted to industry partners.

Protective Test Articles

Test articles are defined as any object that will be exposed directly or indirectly, monitored and evaluated during the blast tests.

Client organizations interested in submitting blast/hazard mitigation test articles for blast exposure will coordinate with ARA directly for PRTC facility access and instrumentation services. All data generated using the test articles will be treated confidentially by ARA unless release is approved by the client.

Description and Discussion of Current Models[1]

CFD (Computational Fluid Dynamics) Models: find numerical solutions to the partial differential equations governing the explosion process. The numerical solutions are generated by discretizing the solution domain (in both space and time). The conservation equations are applied to each of the sub-domains formed by the discretization process, generating a number of coupled algebraic equations that are normally solved by an iterative procedure.

> EXSIM: is a structured Cartesian grid, semi-implicit, finite volume code that relies on the Porosity / Distributed Resistance method for the representation of small-scale objects.

The main effect of these obstacles is to obstruct the flow and generate additional turbulence.

FLACS (Flame Acceleration Simulator) Code: is a finite volume code based on a structured Cartesian grid. The Porosity / Distributed Resistance approach is used to model sub-grid scale obstacles. Transport of scalars and momentum through turbulent processes is modelled using the k-ε turbulence model.

AutoReaGas: is a gas explosion simulator whereas BLAST simulates the propagation of blast waves. The REAGAS and BLAST software were implemented in AutoReaGas as the gas explosion solver and blast solver, respectively.

Advanced CFD Models: improvements on basic CFD models allow an exact geometric representation of the explosion scenario, limited by the available computer memory.

CFX-4: is a general purpose, commercially available CFD that is a finite-volume, structured grid code. To facilitate the modeling of complex geometries the code allows multi-block, non-orthogonal grids.

COBRA: uses an explicit or implicit, second order accurate (spatial and temporal), finite-volume integration scheme coupled to an adaptive grid algorithm. The grid is effectively unstructured and may be refined and de-refined automatically locally within the flow, in principle allowing features such as flame fronts and shear layers to be resolved accurately.

NEWT: is an unstructured adaptive mesh, three dimensional, finite volume (tetrahedral volumes), computational fluid dynamics code.

REACFLOW: is a CFD code designed to simulate gas flows with chemical reactions. It is a finite-volume, unstructured mesh code, which may be used to model two or three dimensional geometries.

Imperial College Research Code: a 2D computer code, for research purposes, which incorporates all the latest findings with respect to the combustion model, a sophisticated gradient/flame front tracking refinement and de-refinement mesh algorithm, as well as using an accurate time (implicit Euler) and spatial discretization (Total Variation Diminishing - TVD) schemes.

Empirical Models: Empirical models are based on correlations obtained from analysis of experimental data. The models described below constitute a selection of methods commonly used in industry for risk assessment.

TNT Equivalency Method: based on the assumption that gas explosions in some way resemble those of high charge explosives

TNO Method: assumes that the whole vapour cloud contributes to the over-pressure, rather than just the portion which happens to be in a confined and/or congested area.

Multi-Energy Concept: assumes that only that part of the gas cloud which is confined or obstructed will contribute to the blast.

Baker-Strehlow Method: consists of plant walk-through to identify potential explosion sites, assess flame speed, fuel reactivity, confinement and dimensionality of the confined areas to work out flame speed with results read from a series of graphs.

Congestion Assessment Method: a decision tree procedure as guidance for estimating the source pressure, taking into account the layout of the plant, e.g. degree of confinement and congestion and the type of fuel involved. The accuracy of the estimations was variable, but the method was designed to yield conservative pressures.

Phenomenological Models: are simplified physical models, which seek to represent only the essential physics of explosions. The greatest simplification made is with respect to the modeled geometry.

SCOPE 3 (Shell Code for Over-Pressure Prediction in gas Explosions) Code: seeks to model gas explosions by representing the essential physics in a simplified form. The model is one-dimensional and is based on the idealized and mixed scale geometry of a vented vessel containing a series of obstacle grids.

CLICHE (Confined Linked Chamber Explosion) Code: developed to study confined explosions in buildings but its use has been extended to modeling explosions in off- and on-shore plant.

Known Resources

EPA, www2.epa.gov/rmp/rmpcomp, the EPA's Risk Management Program (RMP*Comp) tool is a free online program which requires very minimal input. RMP*Comp is a simple tool that steps you through a short list of questions about a regulated substance (such as the amount released) and implements the procedures exactly as specified in the RMP guidance.

FM Global Data Sheet 7-42 (May 2008 Ed.), www.fmglobal.com, Guidelines for Evaluating the Effects of Vapor Cloud Explosions Using a TNT Equivalency Method. Provides a relatively simple set of criteria enabling the user to predict if a VCE is, or is not, possible. Also includes information on what materials, amounts, and conditions might allow for a VCE event, as well as information for completing calculations using TNT modeling methodology.

FM Global Data Sheet 7-42 (Oct. 2012 Ed., revised 2014) , www.fmglobal.com, Evaluating Vapor Cloud Explosions Using A Flame Acceleration Method. Completely revised data sheet replacing TNT analysis methodology with Flame Acceleration methodology to categorize materials and set threshold limits. The information in this data sheet does not supply information allowing the user to calculate a VCE model, but suggests the use of FMG's BlastCalc, a proprietary software modeling system.

GexCon, www.gexcon.com, FLACS (FLame ACceleration Simulator) is modeling software based Computational Fluid Dynamics (CFD). Proprietary software modeling of explosion events, including VCE.

Swiss RE, Ex Tool modeling software based on the TNT equivalency method.

The Netherlands Organization (TNO), EFFECTS, www.tno.nl, modeling based on the Multi-Energy Method. Details, calculations, and examples can be found in the "Yellow Book" Methods for the Calculation of Physical Effects - due to releases of hazardous materials (liquids and gases), 2005.

Baker Engineering & Risk Consultants, Inc., http://www.bakerrisk.com, Blast Wave Target Interaction Modeling (BWTI™) was developed by to simulate the generation and propagation of blast and shock waves and the interaction of such waves with structures. BWTI™ solves a set of integral equations governing an inviscid flow. The set of Eulerian governing equations is numerically calculated on an unstructured grid using an explicit, upwind, node-centered finite volume method with a second-order extension of Godunov's scheme. The unstructured mesh formulation allows irregular geometries to be conveniently represented. An adaptive mesh can be employed. The adaptive mesh allows a refined grid to be employed in the vicinity of the blast wave while using a coarser grid away from the wave, thus ensuring an accurate simulation with reduced computational demands.

Protective Design Center for the U.S. Army Corps of Engineers, www.pdc.usace.army.mil, BlastX code performs calculations of the shock wave and confined detonation products pressure and venting for explosions either internal or external to a structure. BlastX has a user-friendly, menu-driven input module and the capability to provide on-screen and hardcopy plots of pressure, impulse and temperature versus time using the DPLOT code. The code computes the pressure incident to an opening or uses arrays of time and pressure stored on disk files and can treat explosions in parallelepipeds, L-shaped rooms, cylinders, and a general room composed from rectangular panels. The code treats as unlimited number of features (e.g. rooms, openings). A clearing model that produces rarefactions from the edges of walls has been implemented for direct shocks.

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